Comments on a Review of Beam Optics Design
December 11, 2001

Characterization of Main Injector Beam Parameters
Presenter: A. Marchionni

1. (Reviewer: A. Drozhdin) The main parameters of the beam are under investigation. Transverse emittance growth with intensity of the bunch was shown. This function seems is natural and depends on many parameters of accelerator. Unfortunately this parameter improvement takes a years of accelerator work.

   Longitudinal emittance behavior during bunch rotation is under investigation. The momentum spread growth with increasing of bunch intensity was found but not explained. Unusual oscillation of phase of different bunches, shown in the presentation, can be a methodological error of measurements. But most probably it is related to RF frequency shift by a small amount at the moment of phase rotation. Some of the bunches get exactly into the synchronous phase, but others have a small displacement which cause phase oscillations. Any case a reasonable explanation of this effect should be found. It seems that this can be understood and fixed shortly.

OK

2. (Reviewer: A. Drozhdin) If 10^{-4} of the extracted beam loss is a limit for NUMI, this requires to think about the beam halo collimation in the MI. These losses correspond to number of particles in the Gaussian distributed beam at the level of 3.5-4 sigma. Even if the real transverse emittance is about 25 pi mm.mrad (95%), the 4 sigma corresponds to 70 pi mm.mrad. And the beam size is a factor of 1.3 larger compared to a reference value of 40 pi mm.mrad. This may cause losses at extraction. The best solution to control losses in the MI (not only at the beam extraction, but at many other cases) is to design and implement a beam halo collimation system. This system should not be too complicated and expensive.

Such a system may become necessary in the future with slip stacking at high intensity. It is not needed for the re-designed NuMI optics.

3. (Reviewer: E. Harms) The results of the MI extraction studies to date suggest putting some priority on the multi-batch extraction studies. In terms of beam line design, I'd suggest using the current values and scale by a factor of 4 for initial conditions until hard numbers can be obtained.

NLG: This has been clarified somewhat, see:
Main Injector parameters expected during NuMI operation - S. Mishra

4. (Reviewer: C. Moore) A point to keep in mind about the loss on the extraction septa vis a vis an assumed emittance is that the scraping will take place on one

side. Hence if a certain emittance beam scrapes on the Lambertsons it does not necessarily imply that the beam will fit through an equivalent aperture downstream and we also can not assume that the halo will all be scraped away at the Lambertsons.

OK

5. (Reviewer: C. Moore) In terms of the detailed longitudinal loss pattern at the MI-52 Lambertsons it is probably difficult to determine the energy of the loss without a detailed Monte Carlo simulation. If I scale using Table 8.1 of Nikolai's book , "Passage of High Energy Particles through Matter", I find a difference in the location of the cascade maximum of a factor of 2.7 between 8 GeV and 120 GeV. Unfortunately the absolute distances are small (a few feet at 120 GeV) making measurements to tell the energies apart difficult. I have asked the Rad Techs to make a detailed survey the next time they survey the area and we will see if we can make any sense out of the measurements.

OK

Beam Optics Design
Presenter: P. Lucas

1. (Reviewer: A. Drozhdin) A momentum dispersion generated by the vertical bends was the main problem. The spot size increase at the maximum dispersion due to momentum spread of 4×10^{-4} was comparable to the beam size from betatron emittance. The improved optics of the NUMI beam line permits to decrease maximum beam size by a factor of 2. This reduces beam size and divergence at the target and possible losses at aperture restrictions in the beam line and/or reduces requirements to the stability of magnet power supplies.

We agree

2. (Reviewer: A. Drozhdin) A sensitivity analyses of magnets installation and field stability to the beam parameters at the target and at the main detector in Soudan (Minnesota), as well as to the beam loss along the beam line are performed. An additional investigations maybe are needed with respect to ground motion to predict periodicity of the equipment realignment.

The pre-target area is located in bedrock and is not susceptible to ground motion. Ground motion in the Main Injector transport to the pre-target area is possible and can be studied in the future.

3. (Reviewer: A. Drozhdin) Two additional quads in the carrier tunnel improve the beam parameters along the beam line especially in a vertical plane, mainly reducing vertical beam size by about 30% in a few points. But these points are not

critical from the point of view of aperture restriction. At the same time additional quads introduce a lot of complications for the beam line construction, operation and cost. An additional magnets, power supplies and cables, beam diagnostics, including radiation monitors and maybe BPMs, are required. Maybe it is good to have a remote control of transverse position of these quads to limit an access to the carrier tunnel for realignment. Because of these complications I suggest to take a look at the possibility to give up of these quads installation in the carrier tunnel.

We have included quads in the downstream section of the carrier tunnel.

4. (Reviewer: N. Grossman) Peter states that the power supply regulation for the large bends is specified at 100 ppm. This is not strictly true. Simply refer to the Power Supply Specification review presentation and subsequent power supply review presentations and you can see what level of PS regulation is budgeted for based on the criteria in the document "Stability Limits on Bend Fields in the NuMI Primary Proton Beamline, Peter Lucas, June 7, 2001" and then updated to December 5, 2001 and presented to me. Some strings (3) are ~50 ppm and some (4) are around 200 ppm, worst case. It is very likely that the ones at 200 ppm will be close to 100 ppm, but not guaranteed. If we end up using the "JITTER" system, then all strings will be better than 100 ppm.

OK

5. (Reviewer: N. Grossman) Similarly, the quad power supply regulation is mentioned at being better than 0.1% - an order of magnitude better than 1%, where there is concern. This is not technically correct. The quad PS regulate at +/- 0.05% of the maximum current of the PS. Some run at the 200 amp tap, others at 100 amps. If one translates this into +/-% of the operating current, the worst case (based on the previous beamline optics design) was +/- 0.44%. This is not that far from 1%. Obviously the higher the operating current, the better this number, but we are trying to minimize quad currents and thus this may be a problem. These numbers have been quoted previously at the PS Specification Review and the Magnet PS System review. Along these same lines, the trims PS are regulated at +/-0.1% of the maximum current (15 amps). These numbers have been discussed with Peter and Sam and were said to be sufficient, but perhaps we need to revisit this.

OK

6. (Reviewer: N. Grossman) As for the quads in the carrier tunnel, I think this is a complicated decision. From a purely operational viewpoint, we need to fully understand what it would gain us. I think the only way we can tell that is with MARS runs of the beam with and without the quads to see how much is gained with respect to losses in the carrier tunnel. From a cost standpoint, it seems like the best way to go would to put them in some sort of box or some kind of a

partially shielded structure to keep water off them. Then, install them with minimal infrastructure and run with them. When they die, turn them off and leave them there and run without them. This, of course, assumes that the quads gain us something, making it worth doing at this level, but do not gain us enough such that a full-blown infrastructure is warranted and that they are necessary to run.

The current design incorporates "full-blown infrastructure".

7. (Reviewer: E. Harms) With all due respect to the effort already expended and improved beam line design since last time, this line is of sufficient importance that I believe it deserves a fresh look from a second design team. Such a new look should be constrained only by 'hard' limits such as extraction and target points, bend centers, and constrained physical apertures. I could see a new design dividing the line into three sections - matching from the MI into an achromatic section through the carrier pipe and then another match to the target. Such a design may require moving bend elements and adding focusing, but could provide a line with greater room for error.

Beam Physics was asked to take a fresh look at the NuMI Primary Beam design shortly after this review. They came up with the same basic design as the NuMI group – putting devices in the downstream end of the carrier tunnel. For a more complete discussion see: http://www-numi.fnal.gov/numwork/reviews/apr_02.html. NLG

8. (Reviewer: E. Harms) Another plus to looking at a new design for the line could be to make beam movement less sensitive to quad movement, gradient errors, skew dipole roll errors, and beam mis-steering. One can almost certainly expect magnetic elements to shift after installation is complete, particularly in the upstream part of the beam line. If one can avoid downtime by relaxing alignment criteria through a good design, so much the better.

NLG: This has been done, see:
http://www-numi.fnal.gov/numwork/reviews/nov_01.html
and:
http://www-numi.fnal.gov/numwork/reviews/apr_02.html, especially the document:
A FODO-Based NuMI beamline design - J. Johnstone

9. (Reviewer: E. Harms) Avoid putting magnetic elements in the carrier pipe except as a last resort. Environmental conditions sound too harsh. To install magnets and expect them to eventually fail and then run without them is wasteful. If there is no recourse but to add quads, they should have BPM's included.

Quads and BPMs will be installed in the downstream section of the carrier tunnel. Environmental conditions in this region have been upgraded to match those for the Pre Target tunnel. SC

10. (<u>Reviewer: E. Harms</u>) The presented design of the beam pipe/LCW lines support needs refinement. The beam pipe should have stiffer support than what was shown and be mechanically de-coupled from the LCW lines. Keeping the LCW below the beam pipe is certainly a good idea should a leak develop, but will it matter if the carrier pipe is cold and damp to begin with? If there are no powered elements, does the carrier pipe carry only the beam pipe?

DP: The recommendation to isolate the beam pipe from the LCW has been done.

11. (<u>Reviewer: E. Harms</u>) An unrelated but I think pertinent question: is the carrier pipe to be under vacuum? If so, to what level; are there scattering issues which could lead to non-trivial beam loss; how is pumping to be accomplished on such a large volume?

DP: By carrier pipe, I assume you refer to the beam pipe and not the concrete tunnel. If this is correct, the beam pipe is to be under high vacuum to a level that is better (lower pressure) than traditionally used on external beam pipes, but worse (high pressure) than an accelerator vacuum. Jim Klen is to produce an engineering note on the vacuum level in each region of the carrier pipe which details the locations of the 38 or so ion pumps distributed (at great expense) along the beamline.

12. (<u>Reviewer: J. Johnstone</u>) The optics design presented showed how, with the addition of 2 quads in the carrier tunnel, the beam size can be significantly reduced through a few restrictive apertures. That's good. However, should these magnets fail, it was indicated that operations would continue anyway with the remaining quads re-tuned. This plan is apparently motivated by the sundry difficulties presented by accessing the new quads. I find this reasoning puzzling. The desirability of reducing beam size would seem to be self-evident, but, if it has been determined that operation without the 2 quads is also acceptable, one has to question what would be the point in installing them in the first place. Supposing that these 2 quads are to be installed, however, then it was also pointed out that they would not be accompanied by any diagnostics - no BPM's, multiwires, or dipole correctors. I strongly believe this would be a serious mistake -- it would be much better to never install the magnets at all. It is a given that these magnets will be mis-aligned by some unknown amount, and that their gradients will only approximate the design values to within a few percent at best. The largest operational problems would be:
    a. shooting blind down >200' of tunnel from Q107 to these quads;
    b. it will not be possible to steer through the magnetic centers of both magnets simultaneously;
    c. the mis-aligned quads will kick the beam by some amount, and with only 2 correctors in each plane between here & the target, it is not possible to correct the kick & steer through the magnetic centers of the remaining quadrupoles, and;
    d. without at least BPM's & dipole correctors there is no way to determine what the mis-alignments are, or what the true quad gradients are.

The current design includes instrumentation and environmental controls in the downstream section of the carrier tunnel.

13. (Reviewer: J. Johnstone) A good amount of work still needs to be done to adequately characterize the sensitivity of the line to errors. Two analyses that come to mind are:
    a. It was mentioned that arising from a variety of sources, including variation from power supply to power supply, read-back error from the supplies to the control room, and transfer coefficient mismeasurements, the actual quad gradients will only approximate the desired values to within a few percent. It is planned to fine tune the quads by observing beam profiles. I'm skeptical that this approach will work -- it is a very poorly constrained, multi-variable problem. If this remains the preferred technique, however, it should be demonstrated to be feasible with realistic tracking simulations of thousands of particles and randomly distributed quad field errors. (More reliable operational techniques exist for fixing the quad gradients in any case).
    b. Realistic simulations of orbit correction need to be performed. The beamline description should include random distributions of the full complement of anticipated error sources from quad & dipole fields & magnet misalignments. Only then can it be determined definitely that correctors & BPM's exist in the correct numbers & optimum locations.

Done.

14. (Reviewer: G. Krafczyk) If Quads are to be installed in the drift tunnel a serious look at the costs should be done first since this will impact the final decision that Numi will make as to weather the cost of adding quads is worth the added expense.

Done

15. (Reviewer: G. Krafczyk) A serious look at tuning the beam line with the quads installed should be undertaken. The idea that you can steer through both quads in a 200' drift space seems problematic but then I don't have to tune the beam line.

Done

16. (Reviewer: G. Krafczyk) I would think that at the least you would like to have Horizontal and vertical BPM's and both horizontal and vertical correction elements with loss monitors at the quads. Also increasing the cost.

Done

17. (Reviewer: P. Martin) The new optics designs have accomplished the goal of reducing the dispersion and beta functions in the critical regions. While both solutions presented - one with two quadrupoles in the drill-and-blast area, and one without - achieve this goal, the question remains as to which of these to choose. My own opinion is that the one with the additional quads is better, because it reduces the beam size at the end of the NuMI stub, where losses cannot be tolerated. However, the NuMI project must weigh the various benefits and costs to arrive at a decision. If the solution with the quadrupoles is selected, I would recommend enclosing the quadrupoles in boxes to provide protection from the environment. I would also recommend adding Beam Position Monitors at these quadrupoles.

Done

18. (Reviewer: M. Syphers) Can design be modularized at all, to more easily facilitate operation? That is, can the major bends be turned into achromatic sections -- either individually or as a unit -- enabling beta-matching at the ends without being sensitive to beam momentum?

The beam was re-designed by the Beam Physics Dept (J. Johnstone) after this review.

19. (Reviewer: M. Syphers) Need to perform Monte Carlo study(ies) of parameter sensitivities -- quad/bend motion, settings; beam quality variations; diagnostics and beam tuning algorithms, etc.

Done

20. (Reviewer: M. Syphers) The beam line design needs to take into account the layout of diagnostic equipment. The placement of devices such as BPM's, SEM's or Multiwires, loss monitors, etc., needs to be carefully and meaningfully coordinated with the optical design. It was not clear where these devices would go or how they would be used to monitor: a) Main Injector performance; b) beam line performance; c) targeting; ...

Done

Power Supply System Impacts
Presenter: N. Grossman

1. (Reviewer: E. Harms) Power supply regulation requirements should not be loosened unless there is a significant financial impact. More often requirements are later made more stringent. It wasn't clear whether the power supplies were to run DC or ramped (I think ramped? - see Nancy's presentation pp. 2 and 4). Operational experience has shown that this makes a big difference in beam reproducibility and stability - both in terms of power supply regulation and magnet hysteresis. Has this been closely looked at?

We presently target beam for P-Bar production with a regulation system that is an order of magnitude lower than being used for NuMI. The cost of changing to DC on the line will impact the operation cost in both power bill and cooling system. The DC system can have better pulses to pulse regulation because the bandwidth limit changes from 20 Hz to 720Hz but is still limited by the ability to measure both the current and reference. SLH